

Technology Requirements for X-Ray and Gamma-ray Polarimetry

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Exploiting the one
remaining aspect of high
energy radiation that has
yet to be utilized.

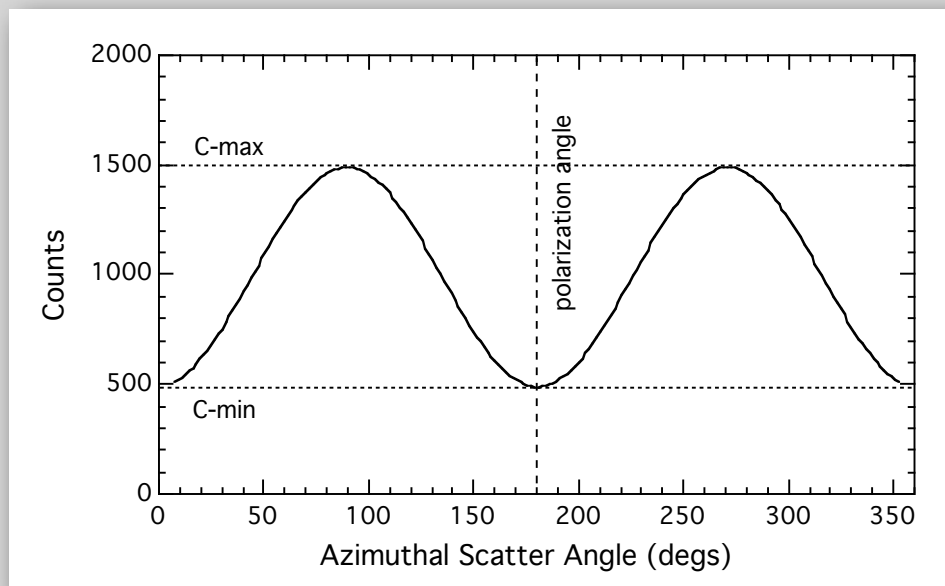
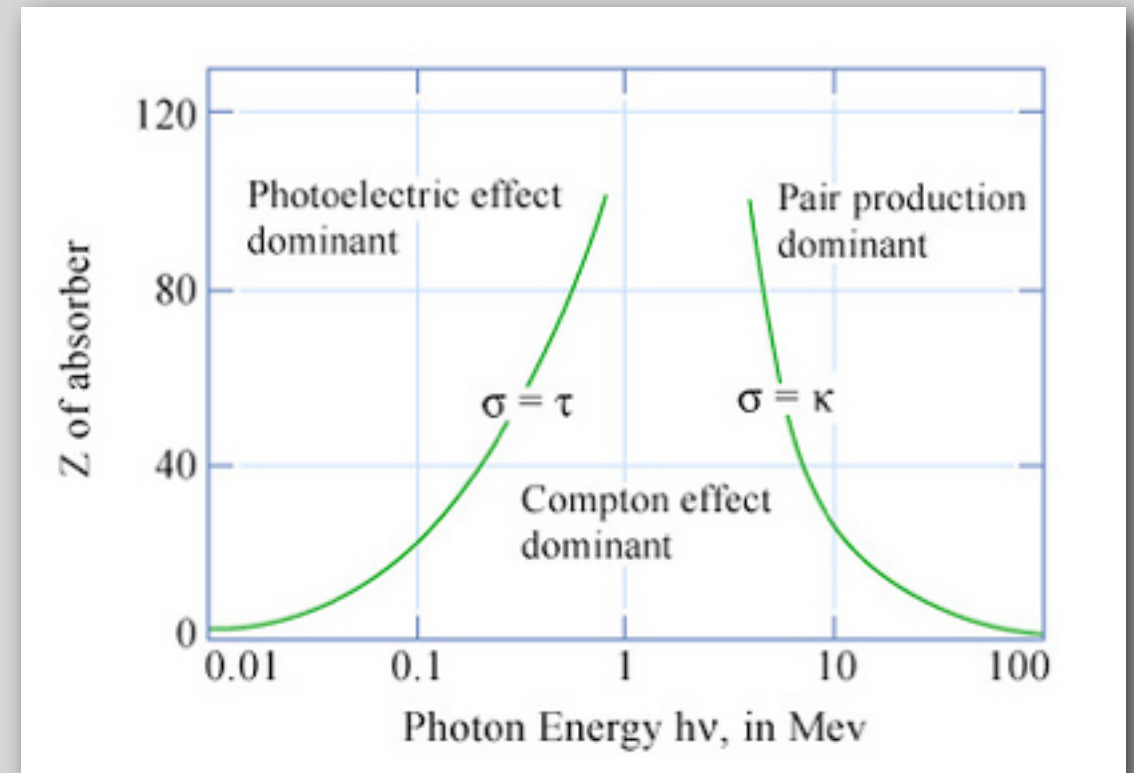
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Peter Bloser (UNH)
Steve Boggs (UCB)
Alice Harding (GSFC)
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Measuring Linear Polarization

0.1 keV – 200 MeV

◆ Several techniques :

- Bragg reflection
- photoelectric effect
- Compton scattering
- pair production



Compton scattering polarization signature.

All of these techniques rely on measuring some asymmetry in the scattered/secondary particle momenta.

Bragg Reflection Polarimetry

Energy Range $\approx 0.1\text{-}10\text{ keV}$

◆ *Measurement Principle :*

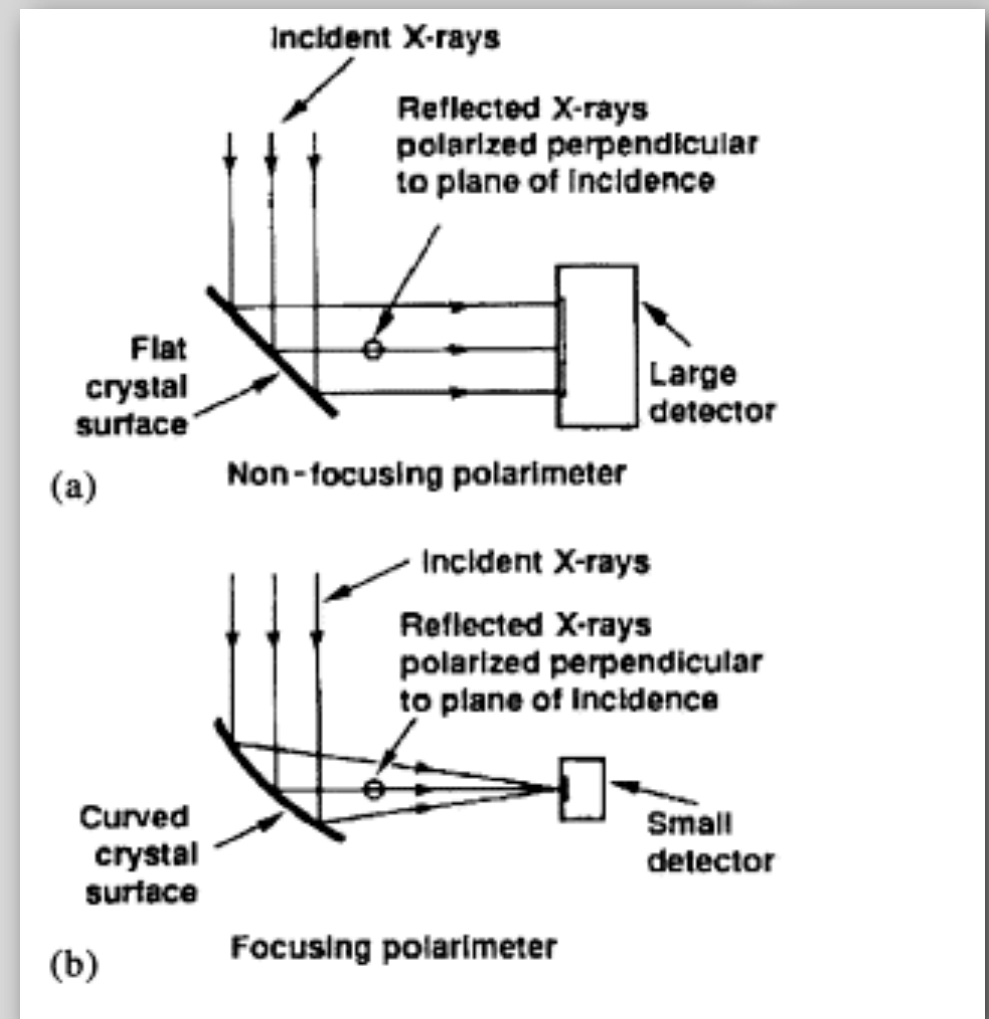
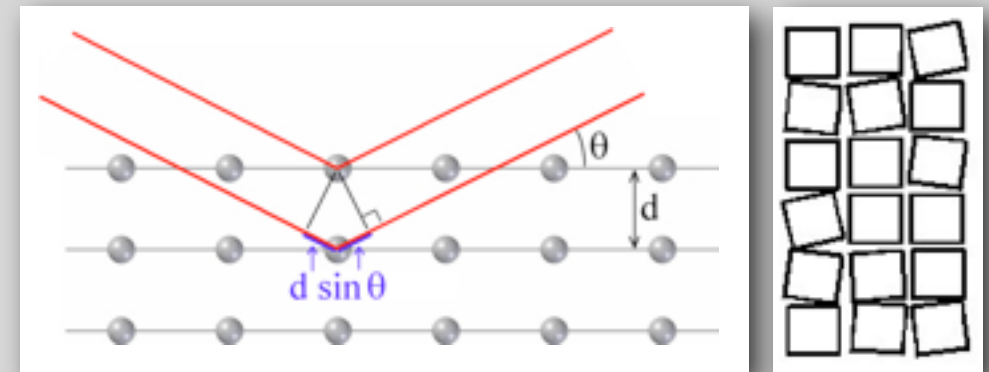
- Preferentially reflects photons whose polarization vector is perpendicular to the plane of incidence.
- photons must satisfy the Bragg condition

◆ *Current Technologies :*

- crystal reflectors
- multi-layers
- requires a spectrometer to measure scattered photons

◆ *Challenges :*

- narrow energy band
- crystal mosaics or graded multilayers (e.g., Marshall et al. 2008) can broaden energy range



Photoelectric Polarimetry

Energy Range \approx 1-30 keV

◆ *Measurement Principle :*

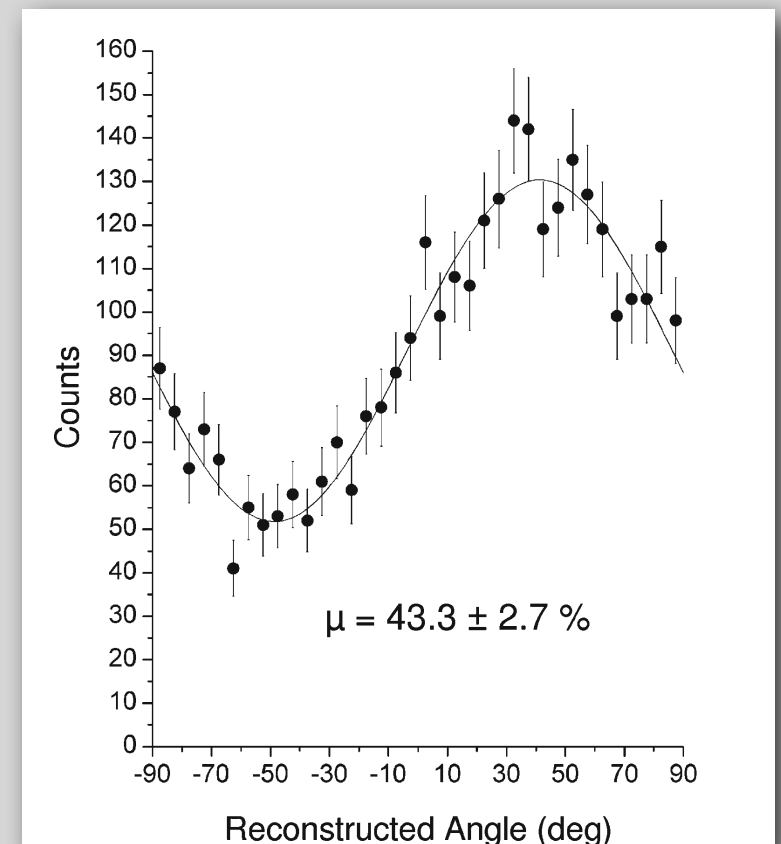
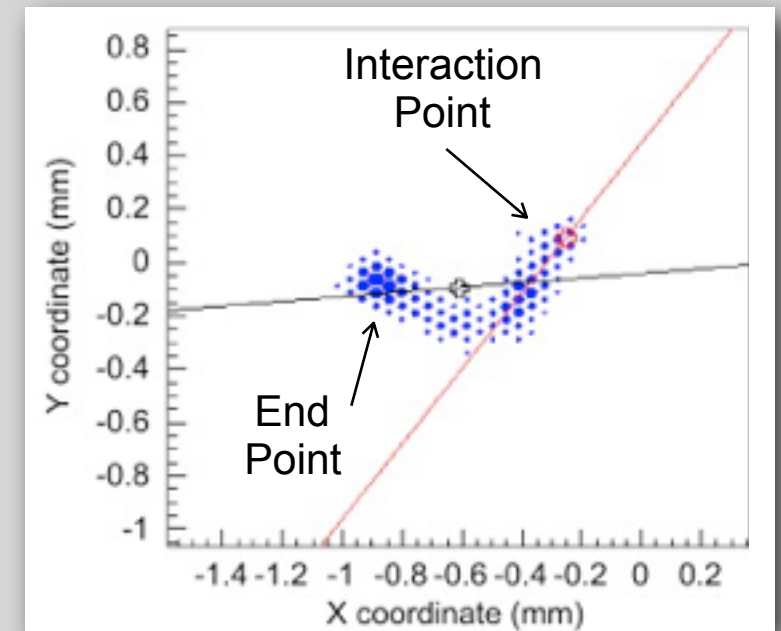
- Photoelectrons tend to be ejected in a direction parallel to the incident polarization vector.

◆ *Current Technologies :*

- CCDs – typically thin, low efficiency
- Gas Pixel Detectors (GPD)
- Time Projection Chambers (TPC)

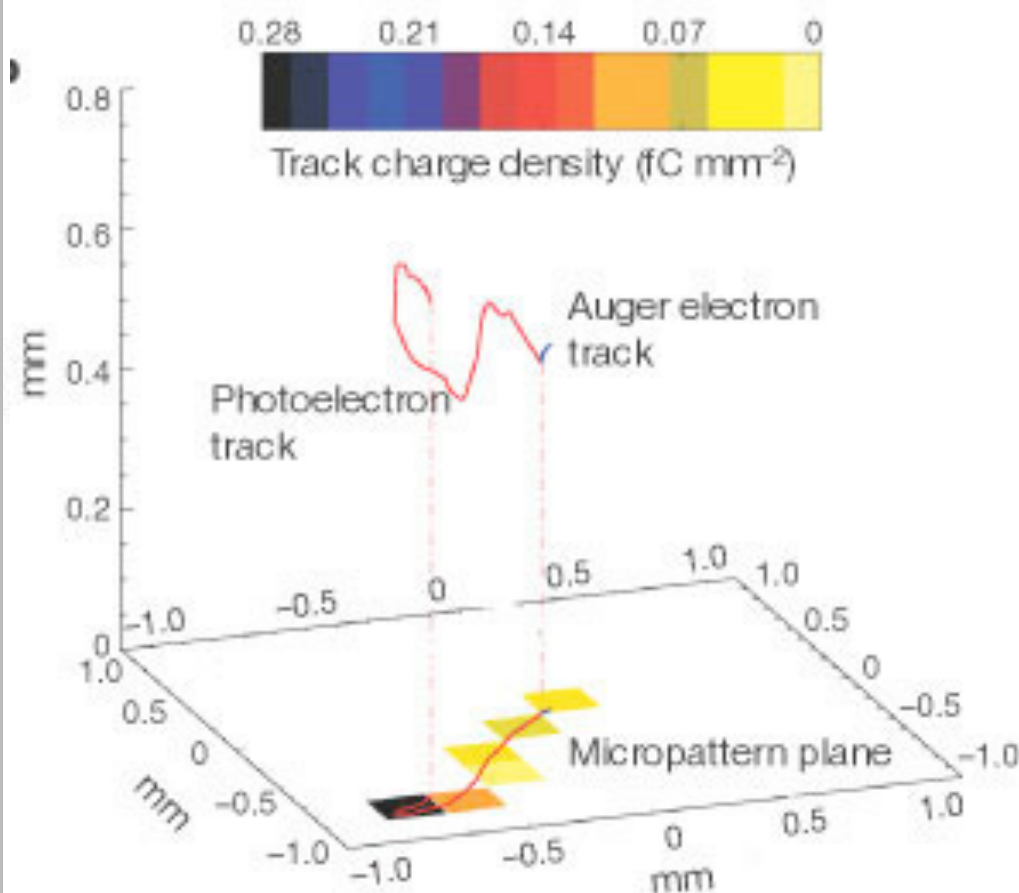
◆ *Challenges :*

- Typical photoelectron range (in gas) is $< 1000 \mu\text{m}$
- Determine initial direction of photoelectron
- Scattering of photoelectron makes it hard to determine the initial direction.
- Isotropically emitted Auger electron can also cause confusion.
- Diffusion of the charge cloud can limit the detail.

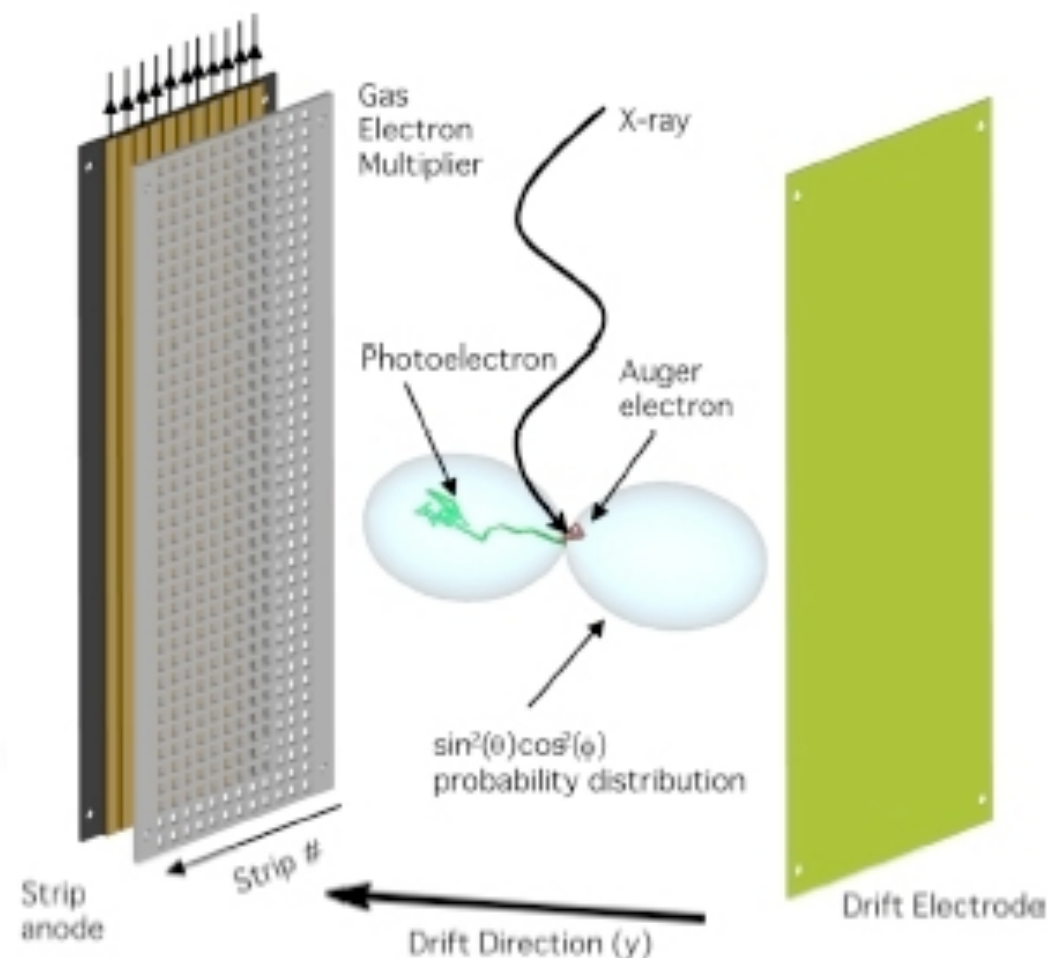


Photoelectric Polarimetry

Two different instrumental approaches:



Gas Pixel Detector
 Costa et al. 2001
 Bellazzini et al. 2006, 2007



Time Projection Chamber
 Black et al. 2007

Couples a Gas Electron Multiplier (GEM) to amplify the ionization track with a finely segmented (2-D) pixel readout. Requires small pixel sizes (< 50 μm) and a large number of readout channels.

Uses time projection to form a 2-D track image from a 1-D strip readout. Geometry gives a diffusion that is independent of interaction depth. Can offer higher energy response.

Compton Scatter Polarimetry

Energy Range ≈ 5 keV - 30 MeV

◆ *Measurement Principle :*

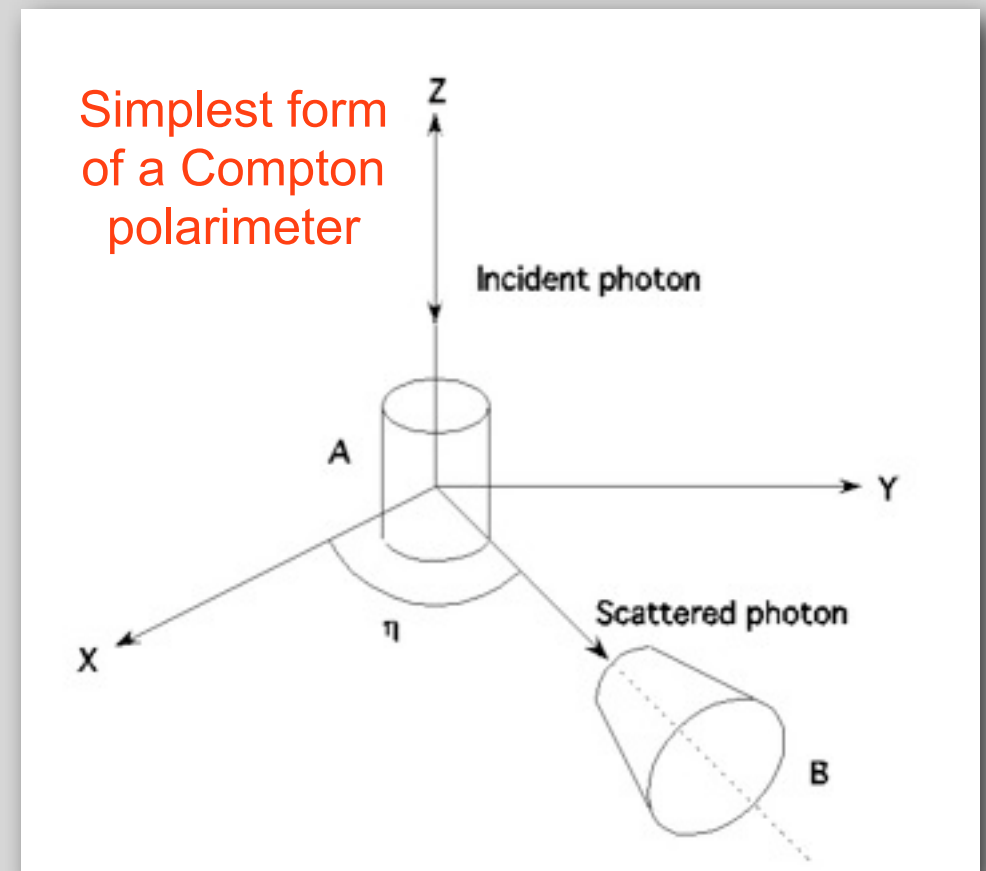
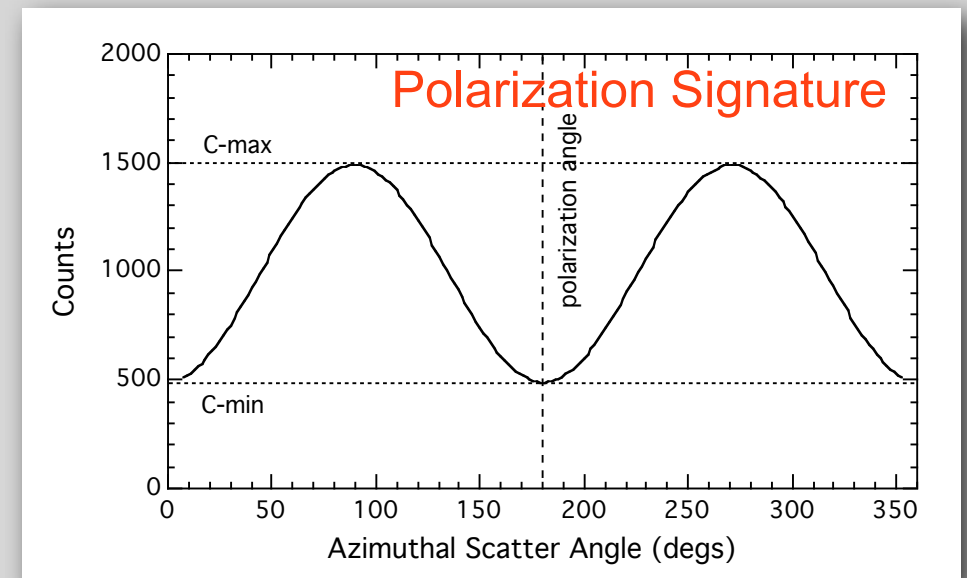
- Photons tend to scatter at right angles to the incident polarization vector.

◆ *Current Technologies :*

- Scintillators
- Solid State Detectors (Si, Ge, CZT)
- Liquid Xe

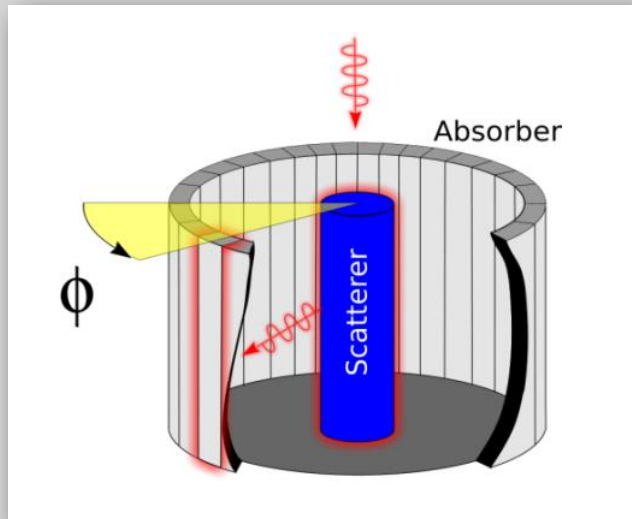
◆ *Challenges :*

- Fine spatial resolution (< 1 mm)
- Energy resolution
- Time resolution (nsec)
- Multiple scattering
- Modulation decreases with energy.

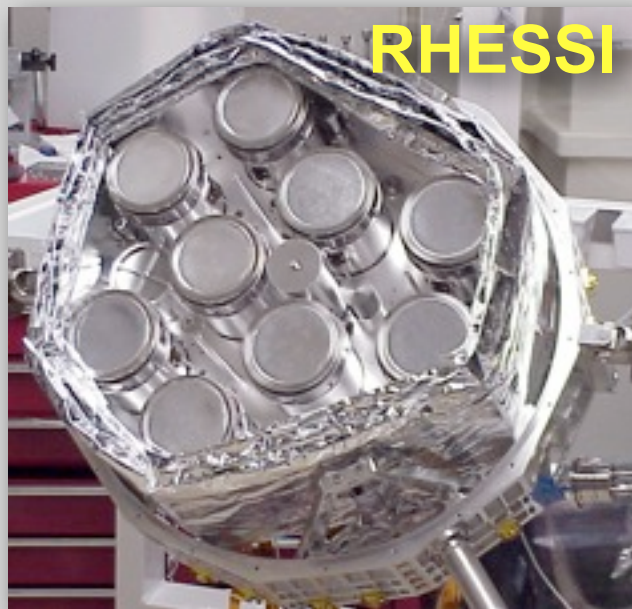


Compton Scatter Polarimetry

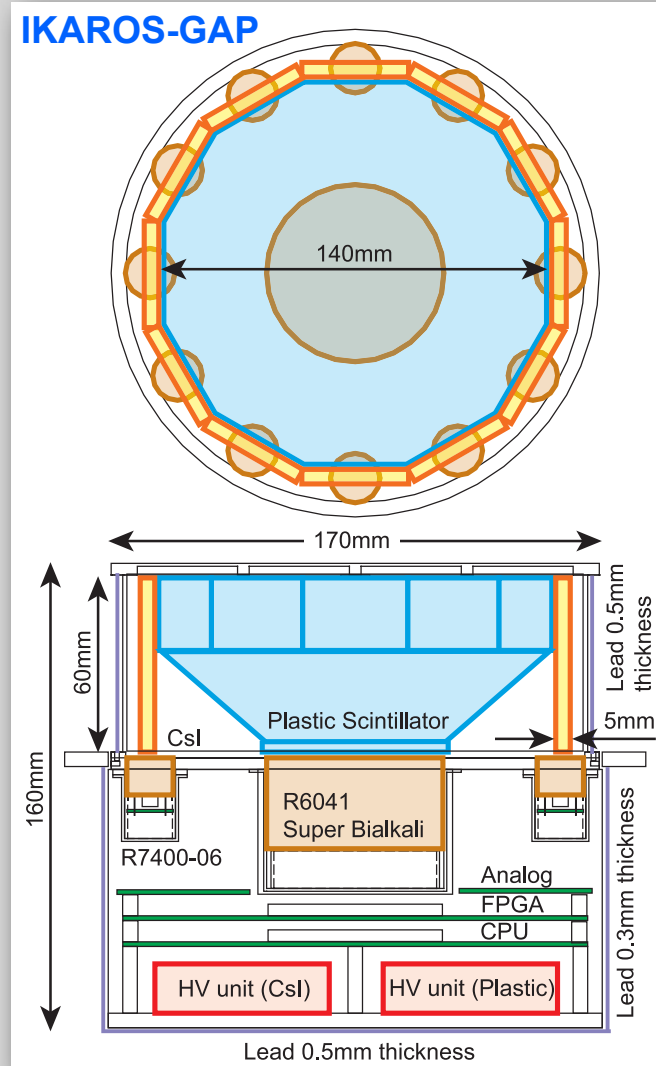
Energy Range $\approx 5 \text{ keV} - 30 \text{ MeV}$



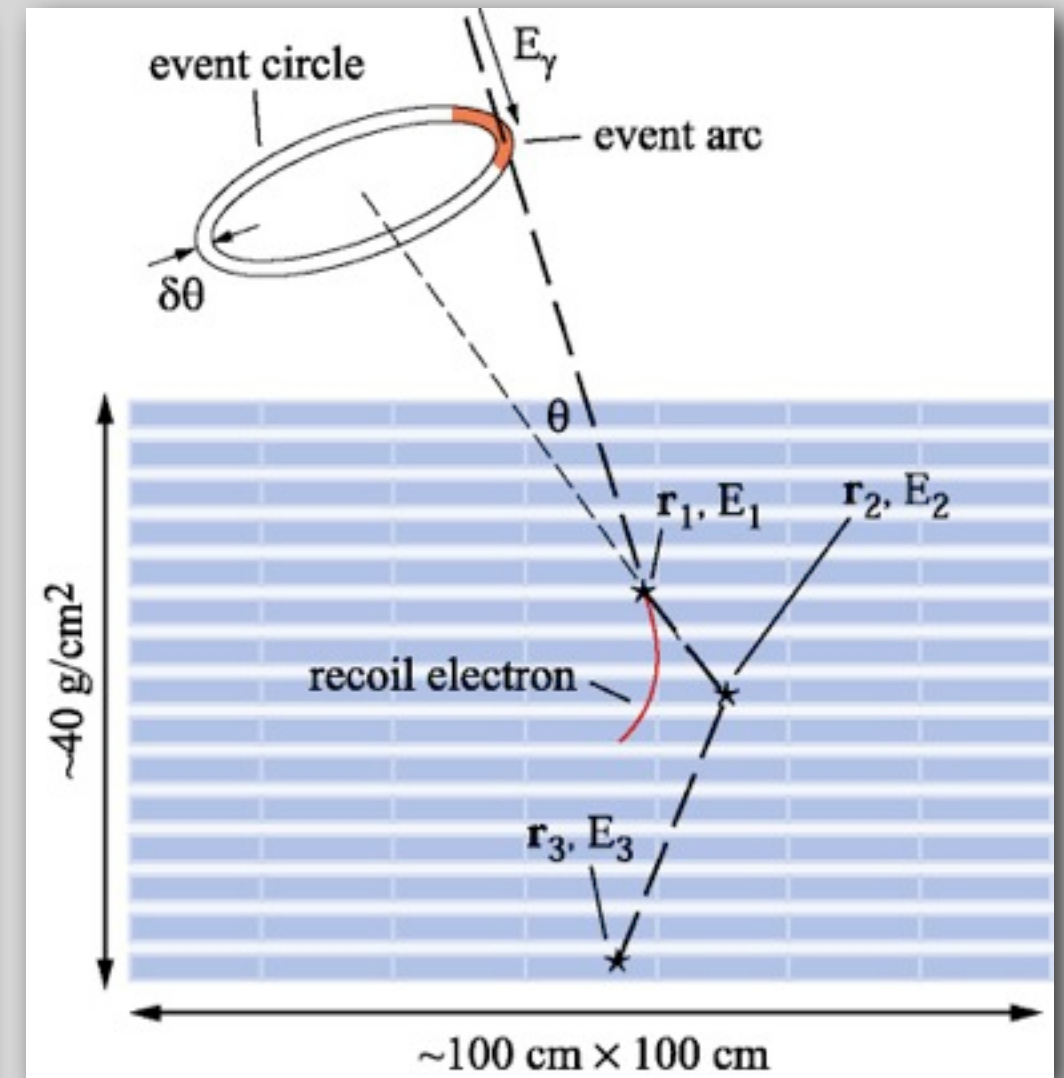
At low energies (Thomson regime) a passive scattering element is used.



At higher energies scattering between two active elements becomes possible.



Some Compton polarimeters are designed with a large FoV to capture GRBs. (Yonetoku et al. 2011)



More advanced designs permit the tracking of a photon through multiple scattering events. At higher energies, event reconstruction is required to determine polarization from initial scattering and to reduce background.

Pair Production Polarimetry

◆ *Measurement Principle :*

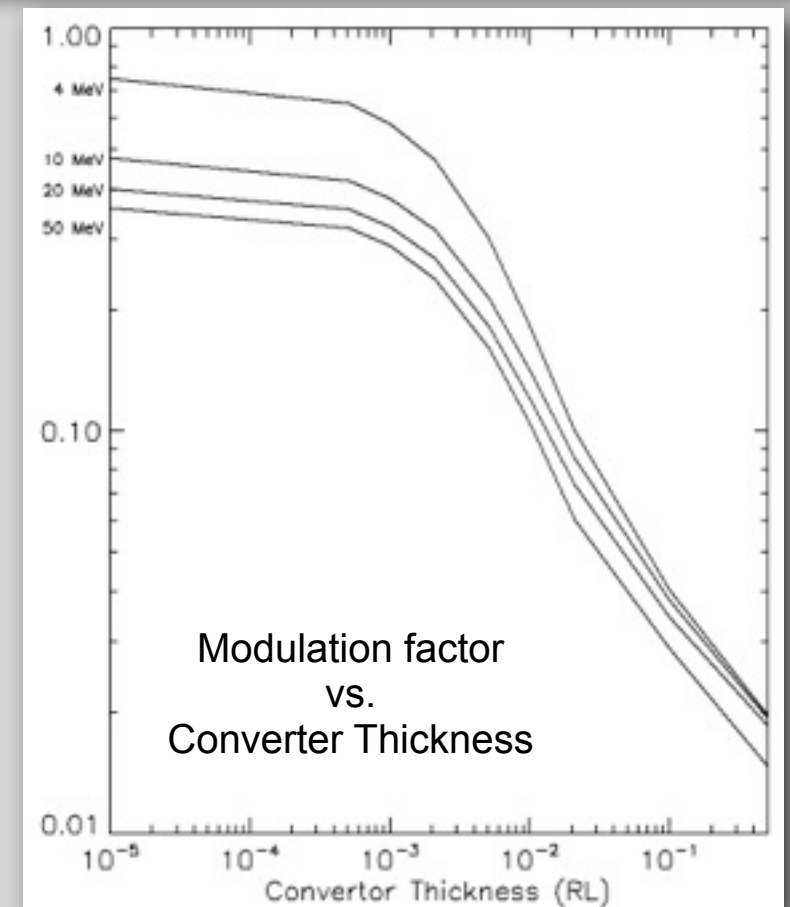
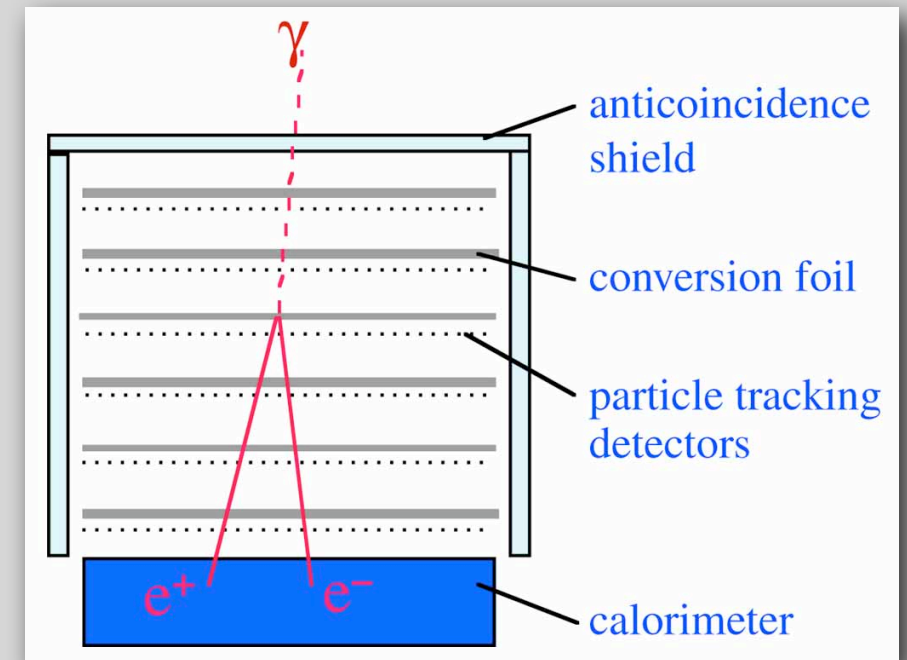
- The plane of the electron-positron pair is related to the incident electric field vector.

◆ *Current Technology :*

- Si tracking (e.g., Fermi)
- Micro well gas detectors

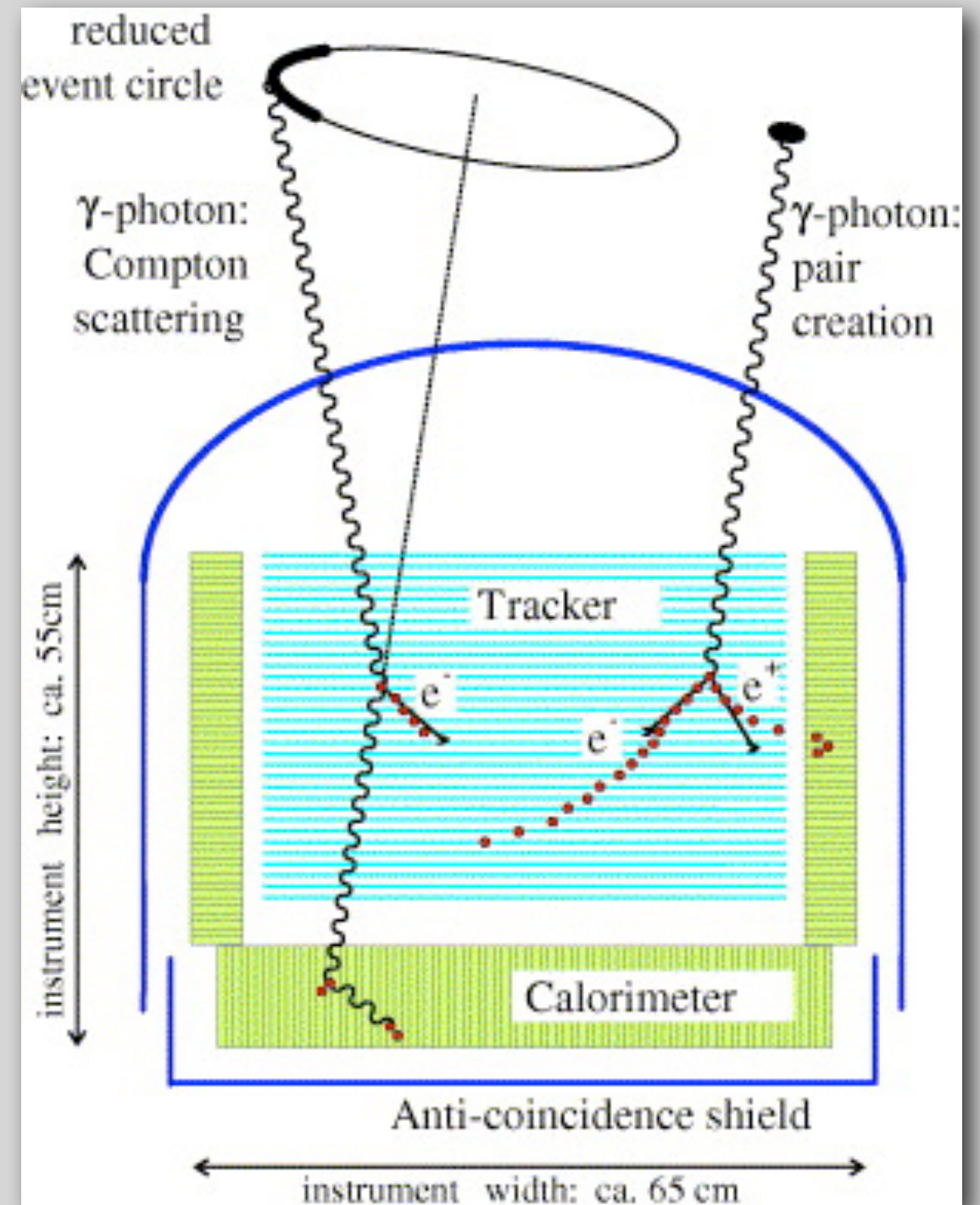
◆ *Challenges :*

- Measure momenta of e^+/e^- pair
- Determine initial directions of e^- and e^+
- Need low density detector to minimize Coulomb scattering to optimize angular resolution and polarization sensitivity
- Triplet production (measurable recoil momentum) offers possibility of much higher angular resolution and stronger polarization signal.
- Identification of e^+ and e^- could also improve the polarization signal.



Imaging Spectropolarimetry

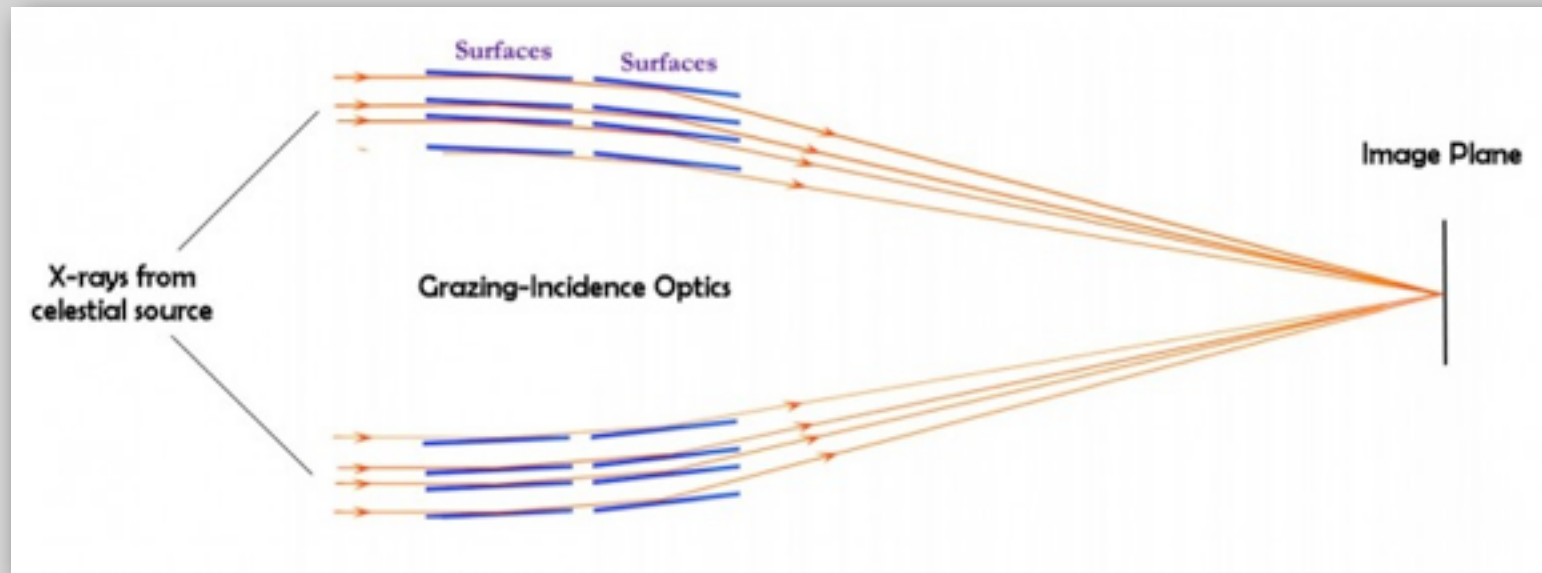
- ◆ In many cases, it would be useful to have simultaneous imaging, spectroscopy and polarimetry.
- ◆ Imaging is not just a means to resolve fine detail, it is also a means to reduce background in a measurement and to distinguish sources in a crowded field.
- ◆ Some types of imaging require a polarimeter at the focal plane.
- ◆ In other cases (Compton and pair production imaging), the imaging process itself provides the polarization measurement.
- ◆ Compton and PP imaging can both cover a substantial fraction of the sky.



A design that utilizes both Compton Imaging and Pair Production Imaging.

Focusing Techniques

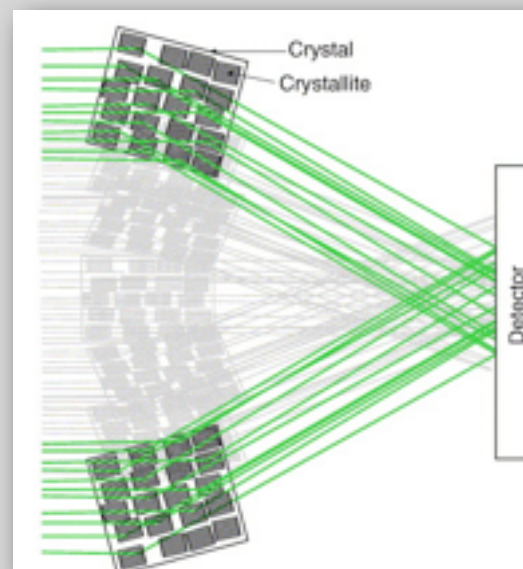
Grazing Incidence Imaging



Current technology can image up to ~80 keV, but higher energies may be possible.

(e.g., Koglin et al. 2004; Koglin et al. 2009; Jahoda et al. 2010)

Laue Lens Imaging



Lenses can be designed for narrow-band ($\Delta E \approx 100$ keV) or broad-band ($\Delta E \approx 500$ keV) imaging at energies below 1 MeV, but can require very long focal lengths (20-100 m).

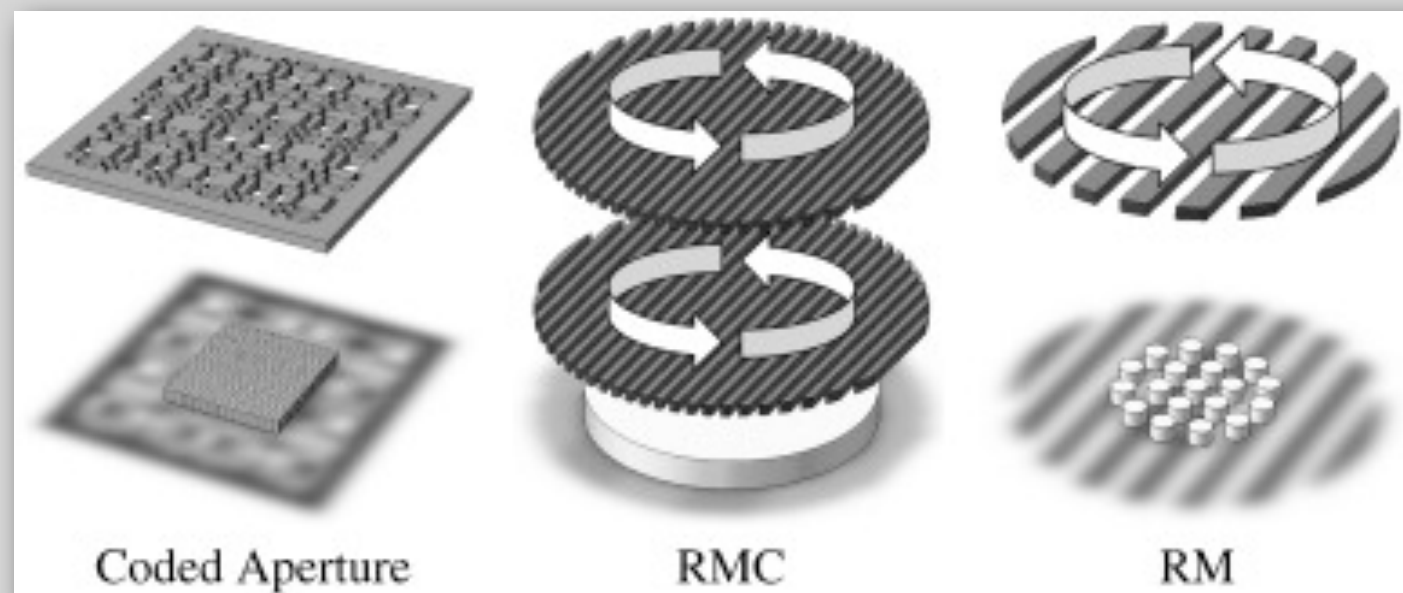
(e.g., Halloin & Bastie 2005; von Ballmoos et al. 2006; Barriere et al. 2009)

Modulation Imaging

- ◆ Spatial modulation of photon flux can provide imaging with resolutions smaller than 1° .
- ◆ Spatial or temporal modulation of photon flux can provide imaging with resolutions smaller than $1'$.
- ◆ Although very fine angular resolution is possible, this approach results in a loss of effective area.

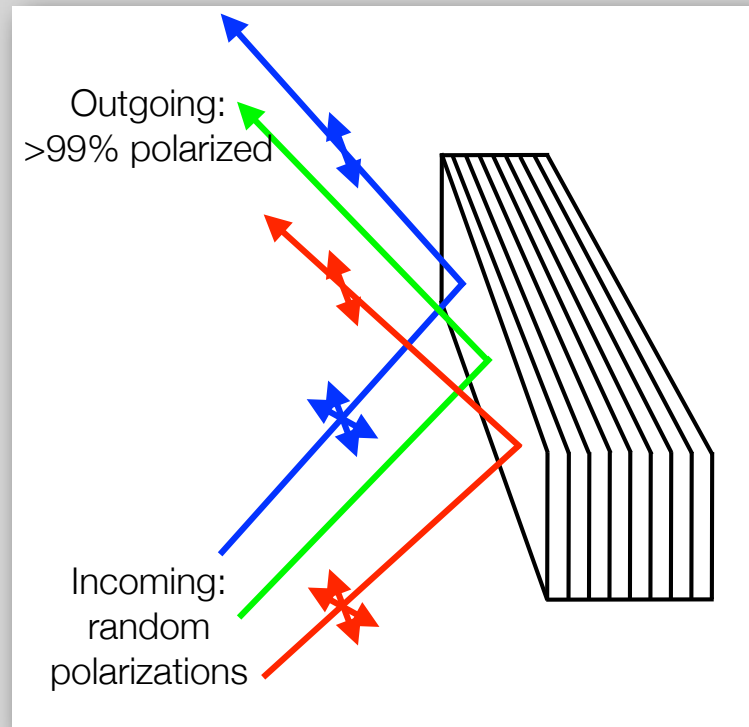
Fine resolution would mostly be of interest for solar flares, separating pulsar and nebula signals, or mapping SNRs.

(e.g., Hurford et al. 2002; Shih et al. 2012)



Bragg Polarimetry (< 1 keV)

(Marshall et al. 2007; 2008)



- ◆ Bragg reflection at Brewster angle (45°) completely polarizes
- ◆ Multilayer coatings give high reflectivity in 0.1-1.0 keV band
- ◆ Coatings have narrow bandpasses but polarized light is likely to be a continuum
- ◆ Disperse with gratings to match ML bandpasses to get broad band

Near term (2-5 yr)

- Propose and launch suborbital system — Objective: MDP $< 10\%$
- Observe BL Lac objects, flaring BH binaries (with low N_H), Isolated NSs

Mid-term (5-15 yr)

- Explorer class mission — Objective: MDP $\sim 1\%$
- Dozens of targets: Quasars, Sy 2 galaxies, Magnetars, pulsars, CVs, etc.

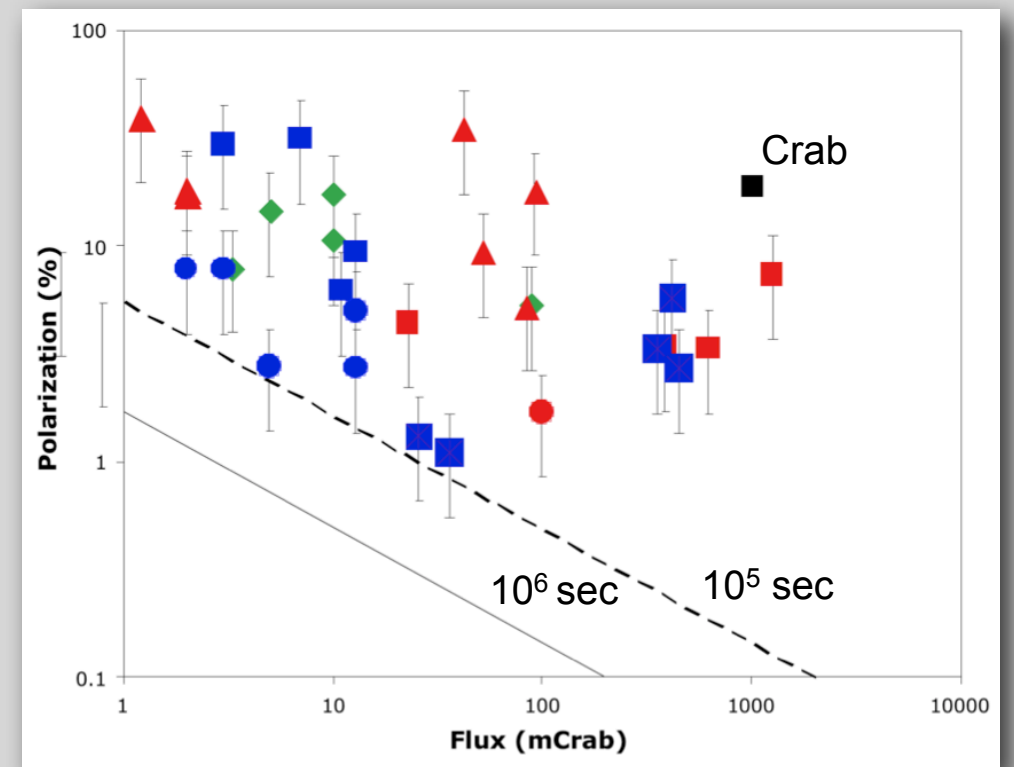
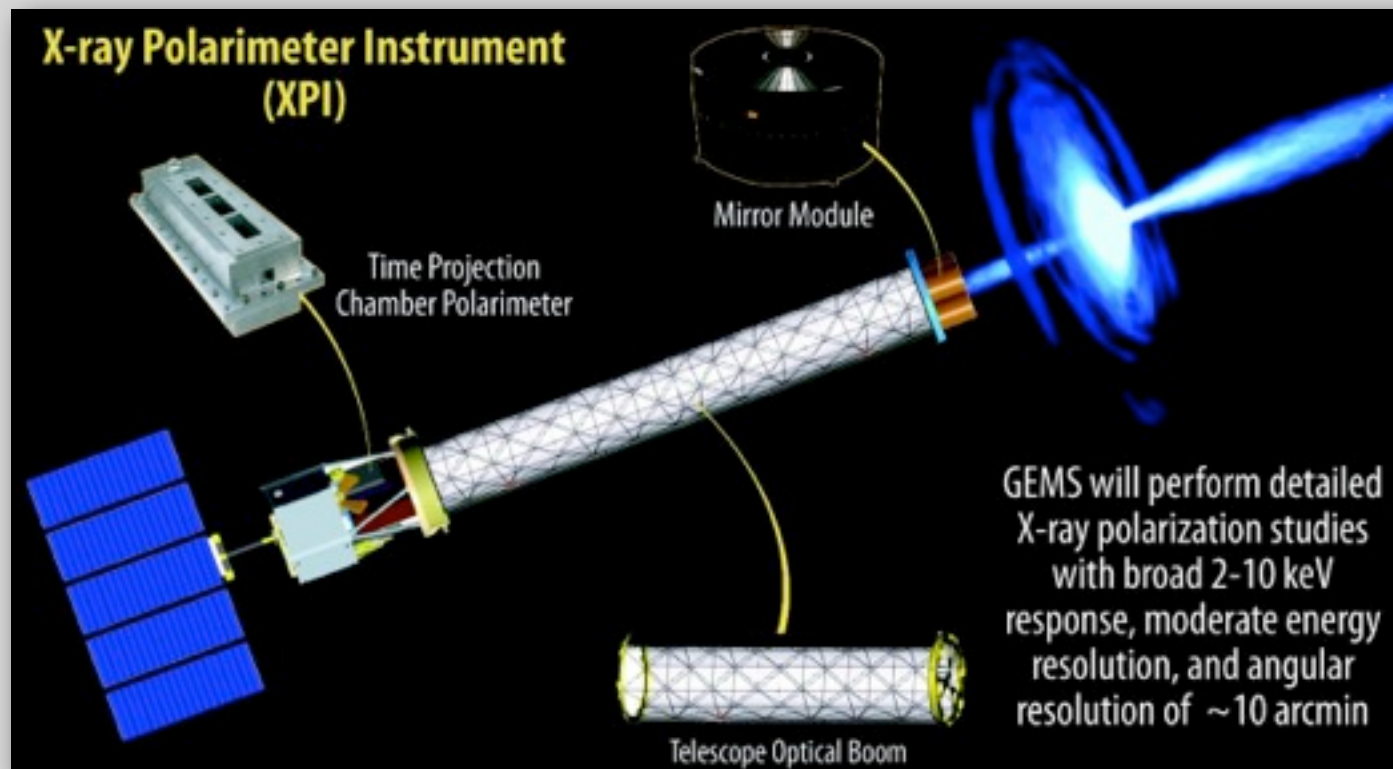
Long-term (15-30 yr)

- Add capability to a large area X-ray observatory

X-ray Polarimetry (< 100 keV)

1st Generation (2020)

(Jahoda et al. 2010)



- ◆ The Gravity and Extreme Magnetism Small Explorer (GEMS) design represents a technology that is currently available.
- ◆ Non-imaging polarimetry (2-10 keV) using a photoelectric polarimeter at the focus of a grazing incidence optic.
- ◆ Observing program included 32 targets (15 black holes; 11 pulsars / neutron stars; 6 SNe remnants).

X-ray Polarimetry (< 100 keV)

metric	1 st generation (~2020)	2 nd generation (~2030)	3 rd generation X-ray
bandwidth	2-10 keV	0.5-80 keV	0.1-80 keV
dE/E	0.2	0.05	0.01
collecting area (cm ²)	500	3000	50,000
Angular resolution (arcsec)	10 arcmin	10 arcsec	1 arcsec
pol. sensitivity (# of sources with $P < \delta$ in 100 ksec)	S>60mCrab N(1%)~5-10 N(10%)~100-1000	S>10mCrab N~10-100 N~10 ³ -10 ⁴	S>0.6mCrab N~100-10 ³ N~10 ⁵ -10 ⁶
Historic analogy	Uhuru (1970)	Exosat (1983)	Chandra (1999)

relevant concept

GEMS

BEST

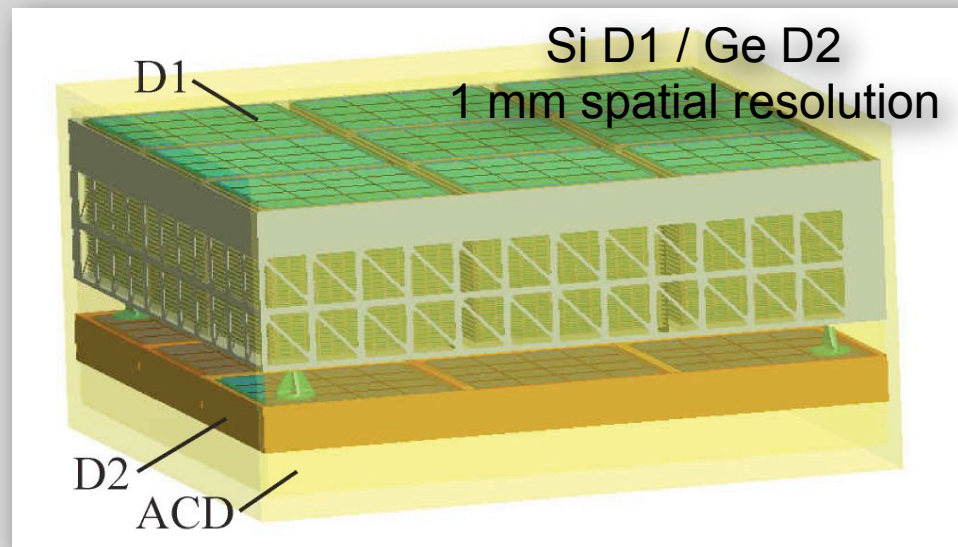
IXO

Gamma-Ray Polarimetry (0.2 - 30 MeV)

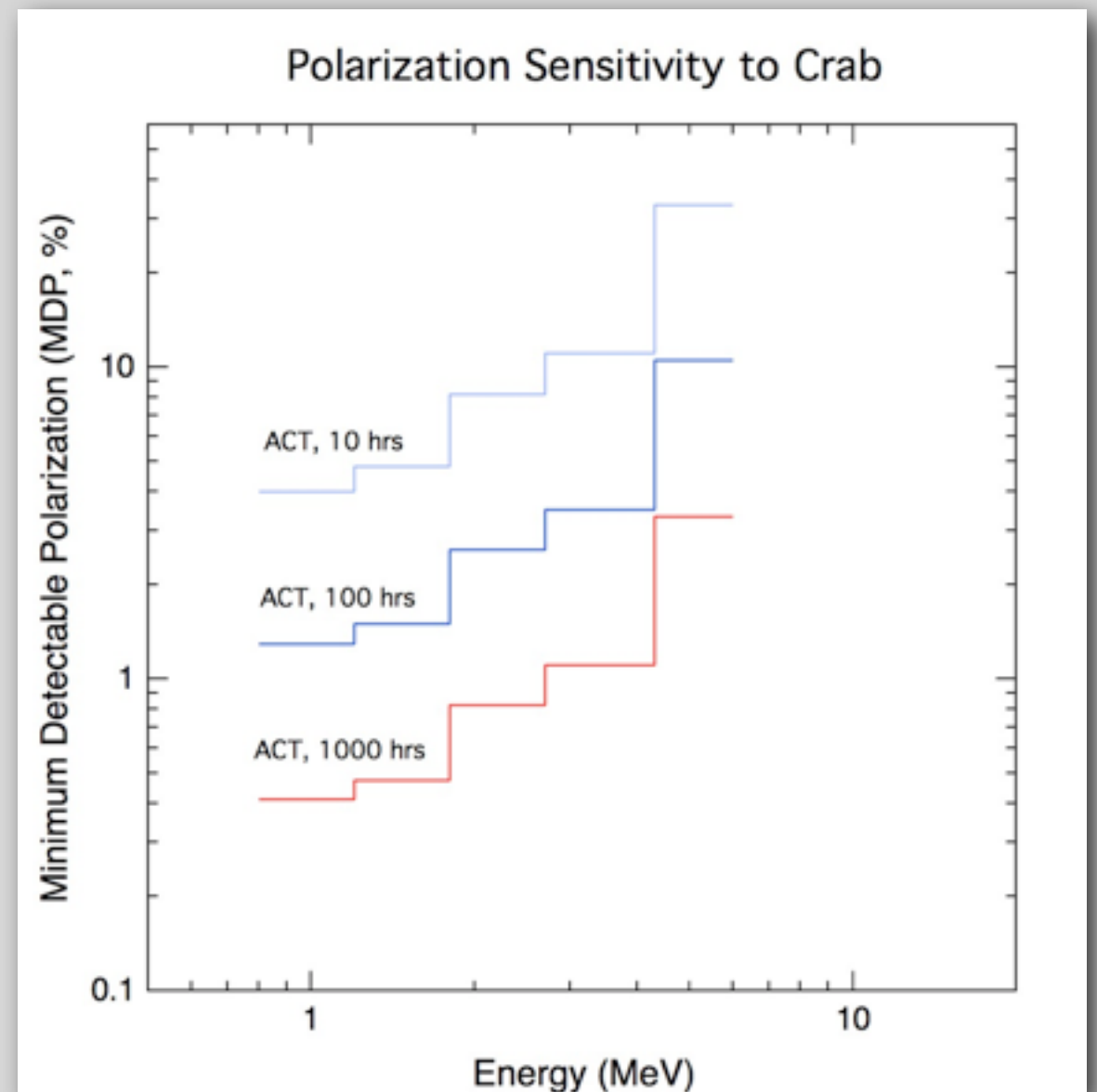
1st generation (2020)

(Boggs et al. 2006)

The Advanced Compton Telescope (ACT) design (2005) represents technology that is currently available.



Energy Range	0.2 - 10 MeV
Angular Resolution	1°
Effective Area	1000 cm ²
No. of Sources	~1000



Gamma-Ray Polarimetry (0.2 - 30 MeV)

	1st Generation (2020) - ACT	2nd Generation (2030)	3rd Generation (2040)
Energy Range	0.2 - 30 MeV	0.2 - 30 MeV	0.2 - 30 MeV
Angular Resolution	1°	30'	10'
Energy Resolution ($\Delta E/E$)	<5%	<2%	<1%
Effective Area	1,000 cm ²	5,000 cm ²	10,000 cm ²
No. of Detected Sources	~1000	~5,000?	~10,000?
Polarization Sensitivity* (MDP) - 10 ⁶ sec	<10% MDP 100 mCrab	<4% MDP 100 mCrab	<2% MDP 100 mCrab

*3 σ MDP extrapolated from estimates for NCT balloon payload (Chang et al. 2007)

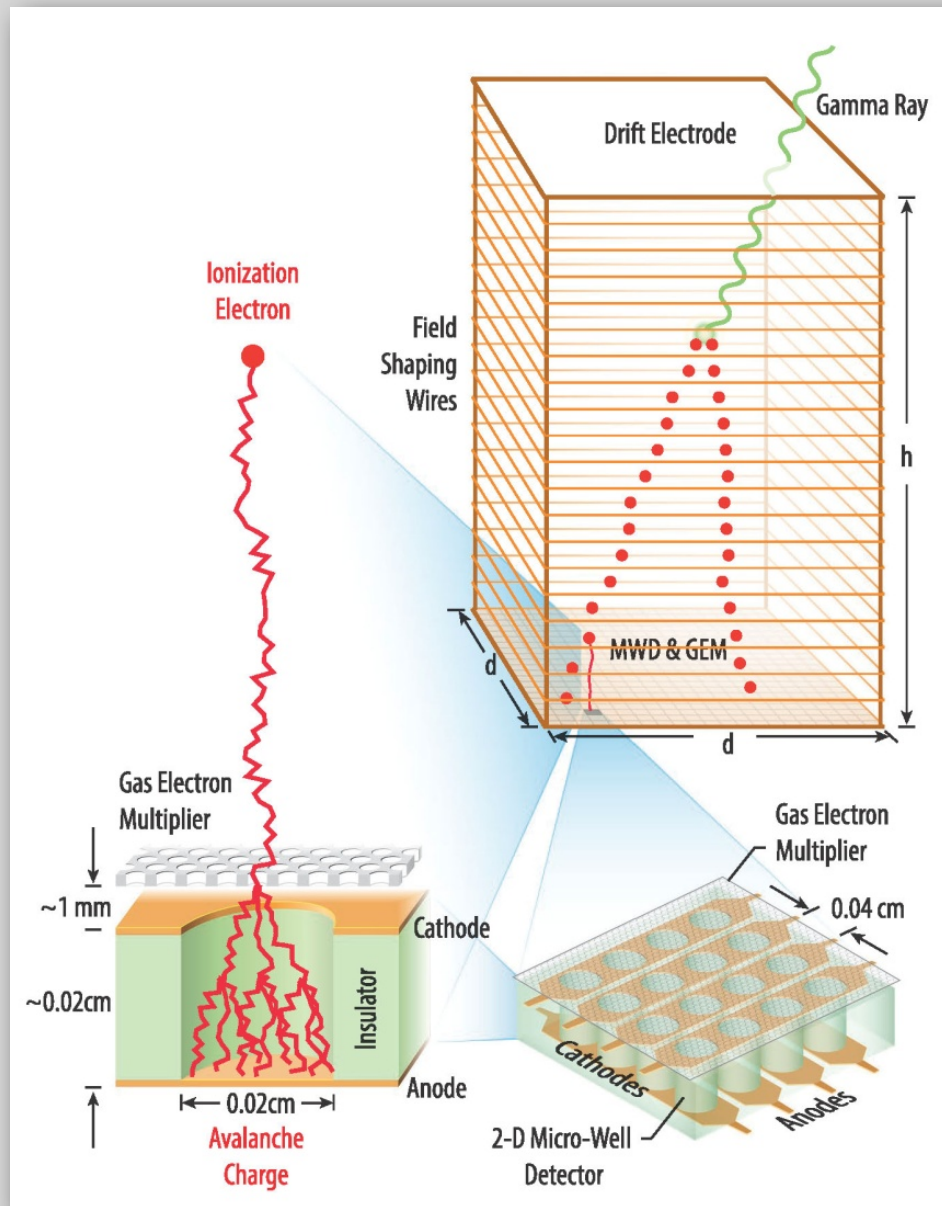
Gamma-Ray Polarimetry (5 - 200 MeV)

1st Generation (2020)

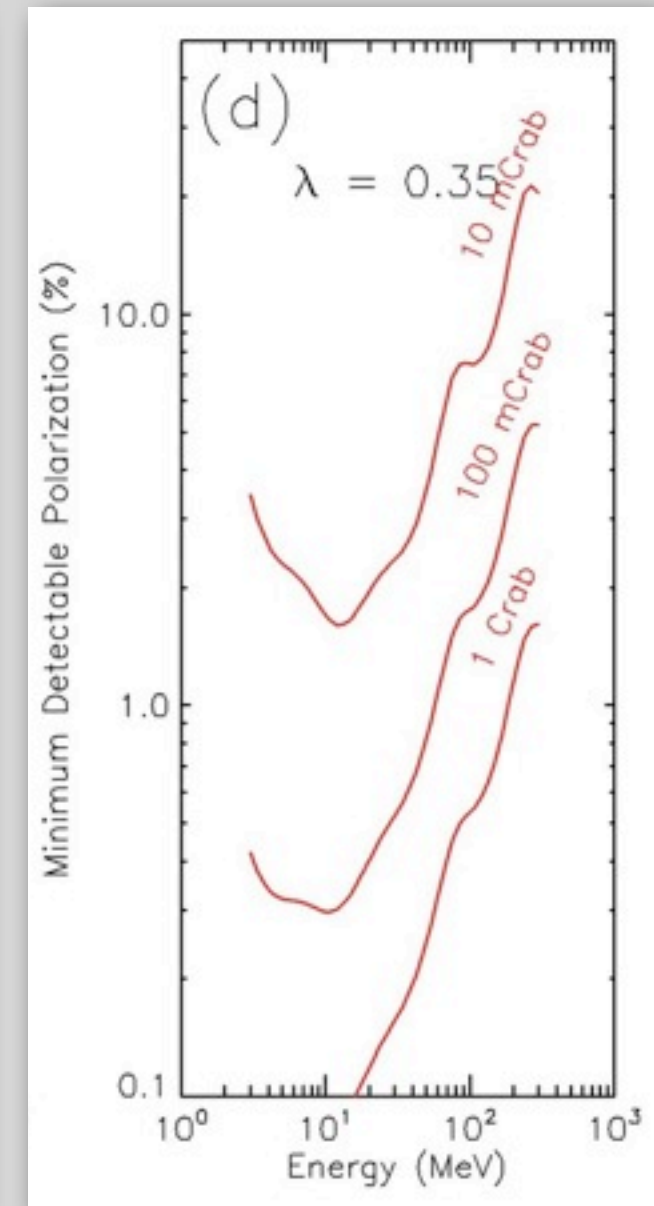
- ◆ 8 m³ active volume
- ◆ ~1° angular resolution
- ◆ MDP < 5% for 100 mCrab

2nd Generation (2030-2040)

- ◆ Inflatable ~10³ m³ volume
- ◆ ~1' angular resolution
- ◆ MDP < 1% for 100 mCrab



Large volume Time Projection Chamber (TPC). Low density optimizes polarization sensitivity.
(Hunter et al. 2010)



MDP of an 8 m³ detector for 100 hour observation

General Technology Issues

- ◆ *Modulation Factor*
This is a figure-of-merit that defines the intrinsic quality of a polarization measurement.
- ◆ *Systematic Effects*
A variety of systematic effects (instrumental asymmetries) can mimic the polarization signature. Rotation is often used to minimize these effects, but in some cases this is impractical.
- ◆ *Effective Area*
Larger effective areas will be required not only for source detection, but also for time-resolved and energy-resolved studies of brighter sources.
- ◆ *Electronics*
Large number of channels, high speed, low power, fast timing.
- ◆ *Imaging polarimetry*
In many cases this is a means to improve S/N rather than to provide fine structure. But as the number of detected sources increases, imaging will be essential for resolving source confusion.
- ◆ *Dedicated Mission vs. Shared Focal Plane*
Some concepts involve sharing the focal plane of an X-ray imaging system (e.g., IXO). This may not be an effective approach for advancement of polarimetry.

What about circular polarization?

